A Comparative Analysis of the Seismic Response of Nearby Tunnels and Bridges

A COMPARATIVE ANALYSIS OF THE SEISMIC RESPONSE OF A NEARBY TUNNEL AND BRIDGE.

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Abstract: *A common perception regards the expected high robustness of tunnels to seismic events, especially those excavated in hard rock. Indeed, on the one hand, recent works have highlighted that both underwater and mountain tunnels might not be as earthquake-resistant as once expected. Nevertheless, on the other hand, they generally suffer much less seismic damage than above-ground structures and infrastructures. In any case, a direct comparison of the actual response of side-by-side above- and underground infrastructures is still missing. This study investigates the seismic responses of a nearby bridge and tunnel (located in the San Francisco Bay Area), focusing on one near-fault earthquake and considering different structural parts of the bridge super and substructure. The experimental evidence is used to compare the dynamic behaviour of these strategic infrastructure assets.*

Keywords: *Seismic Response, Bridge Monitoring, Tunnel Monitoring, Earthquake Engineering, Architectural heritage of the 20th century.*

1. Introduction

In the scientific literature, there are several seismic analyses of the behaviour of bridges (Mccallen et al., 2005) (Jiang et al., 2020) and submerged tunnels (Dikmen, 2016; Di Pilato et al., 2008; Martinelli et al., 2010). Yet, apart from a few qualitative analyses – e.g.(Bana e Costa et al., 2008) –, there is a lack of quantitative data about comparing these two types of infrastructures.

The analysis reported here is focused on the Transbay Tunnel and the East portion of the San Francisco-Oakland Bay Bridge. Both represent two major civil engineering and architecture achievements of the 20th century, endangered by the highly seismically prone area where they are inserted.

The study aims to determine the behaviour of these two worldwide famous infrastructures in the transversal direction under seismic solicitation from near-fault earthquakes. The main advantages of focusing attention on these two case studies are that they are in the same area and, more importantly, in an almost parallel arrangement.

The study is based on data recorded by The *Centre for Engineering Strong Motion Data* (CESMD). For both infrastructures, the acceleration records were obtained from the monitoring systems installed on them.

2. The case studies of the Bay Bridge and the Transbay Tunnel

2.1 Bay Bridge

The Bay Bridge was designed by Charles H. Purcell and built between 1933 and 1936 by the American Bridge Company. It opened to traffic on November 12 of the same year. Above the bridge it runs Interstate 80 which approximately, as of the early 2000s, carries 260,000 vehicles per day (Nicolas Janberg, 2006).

The San Francisco-Oakland Bay Bridge was initially composed of two different structural typologies: in its portion at East of Yerba Buena Island it was composed of a double tower span, five medium truss spans, and a 14-section truss causeway, while in the West part, it was (and still is) a suspension bridge. The East part was damaged during the Loma Prieta earthquake (1989, with a moment magnitude Mw= 6.9 and a surface wave magnitude Ms=7.2) in which the most severe damage was the unseating of the top and bottom deck from their positions (*The Loma Prieta, California, Earthquake of October 17, 1989, Highway Systems*, 1998.). This was a very relevant event; indeed, the 1989 Loma Prieta earthquake caused 43 reported deaths, due to multiple bridge collapses throughout California, to which the Caltrans authority responded by greatly expanding its bridge research program. This also led to the later establishment of the Pacific Earthquake Engineering Research Center (PEER) Bridge Research Program.

For the East part of the San Francisco-Oakland Bay Bridge in particular, the consequent intervention of retrofitting has pointed out the need for a new superstructure typology. The new East part is composed of 4 different main structural components: the Yerba Buena Island transition structure, the self-anchored suspension bridge, the skyway and the Oakland touchdown. Focusing on the skyway, the part of interest, it is a precast concrete box girder joined through tendons, connected to a concrete pier table. This portion of the bridge is 2085 meters long and it is composed of 13 spans. The planar configuration of the infrastructure is curved at the ends and straight in the midst.

The substructure is composed of a single concrete hollow column for each pier, while the foundations consist of pile caps that are composed of cast-in steel shell concrete piles with a diameter equal to 2.5 meters found in firm old mud below the soft one (Nader et al., 2000) (*SCHEMATICS 58601*, 2014).

During the intervention on the East part of the Bay Bridge, it was instrumented with 73 sensors positioned along its length and at different structural elements of the bridge. In a few piers, such as the one selected here, these sensors are located throughout the whole height, from the pile foundations up to the deck. The purpose of these sensors is to measure the acceleration in three directions: longitudinal, transversal with respect to the axis of the infrastructure, and vertically.

2.2 Transbay Tube

The Transbay Tunnel is a submerged railroad tunnel that connects San Francisco and Oakland, running through the San Francisco Bay, built by the District's General Engineering consultants, Parsons-Brinkerhoff-Tudor-Bechtel, a joint venture that was constituted to manage all technical and construction aspects. The tunnel was opened in 1974, side-by-side with the aforementioned San Francisco–Oakland Bay Bridge, (opened in 1936), as can be seen in Figure 1.

It was built using the immersion tube technique, where a trench was excavated in the bay muck and the prefabricated tubular steel and reinforced concrete segment were first immersed adopting construction barges and then covered with a layer of rock, sand, and gravel.

The tunnel is composed of 57 sections, with an average length of 100 m, a height of 7.3 meters, and 15 meters width. The section is composed of two separate train tunnels separated by a pedestrian gallery in the centre, used for emergency purposes.

The maximum depth of the tunnel is -41 meters below sea level. The Transbay Tube is 5.8 kilometres long and at the end is connected by two boring tunnels with an extension of 5.1 kilometres, excavated in the hard rock of the Berkeley Hills. Importantly, the connection is made with massive joints that have been designed to let the tunnel shake but not break during major earthquakes. These joints are constituted of steel cables and Teflon, and they allow movement of up to 152 millimetres in all directions. When completed, in 1967, the tunnel was the fourth longest vehicular tunnel in the U.S.

Furthermore, in the early 2000s, the tunnel underwent seismic retrofitting, to limit the tube movement in case of sand and gravel liquefaction. The retrofitting intervention consisted of the compaction of the sand and gravel and the use of concrete encase supports on both sides of the tunnel (Michael Cabanatuan, 2004).

The Transbay Tube is instrumented with 40 sensors along its length, which measure acceleration in three directions: longitudinal, transversal with respect to the axis of the infrastructure, and vertical.

***Figure 1**: Approximate route of Transbay Tube, highlighted in yellow, with Oakland/Alameda on the left, San Francisco (Financial District) on the right, and the Bay bridge almost parallel in its easternmost tract. The black row indicates the pier of interest (E6E). Modified from: https://en.wikipedia.org/wiki/Transbay_Tube#/media/File:Transbay_Tube_Route_(2).svg.*

3. Geological and seismic characterization of the area

The area is characterized by a shallow stratum of Young Bay Mud (YBM) with an underlying stratum composed of Old Bay Clay (OBC) associated with older marine and alluvial deposition. The YBM layer has a depth ranging between about 6 and 37 meters, that consists of a normally consolidated, organic-rich marine clay. This material exhibits very low shear strength and is prone to squeezing in case of seismic events.

Conversely, the OBC is an over-consolidated layer with better shear resistance than the YBM. Towards the East flank of the Bay, there is a transition from marine-deposited clay to alluvial sands with clays. These strata are characterized by a higher density and stiffness (Core Capacity Transit Study, 2015).

The Bay area is included in a region that in the last century has been subjected to several strong earthquakes since it is affected by several active tectonic faults. So, it is a high seismic zone, even if none of these faults cross directly the bay.

The seismic event that is analysed in this study is the Berkeley Earthquake of 04 January 2018, which had a magnitude of Mw=4.4 and a depth of 12.3 kilometres. Since most of the structures in the area were properly seismically designed, no large damages were reported. Considering the population report that is available on the CESMD website the quake has been described as a class V on the Modified Mercalli Intensity (MMI) scale, based on reports from the inhabitants of Berkeley and the surrounding areas.

Importantly, the epicentre was only 8.51 km and 10.78 km away from the two infrastructures (considering the position as per the longitude and latitude assigned to the respective stations in the CESMD dataset). Of course, such very near-fault ground motions tend to increase the expected damage to civil structures, if compared to ruptures of the same intensities but originated further afield.

4. Study of the behaviour of the two infrastructures

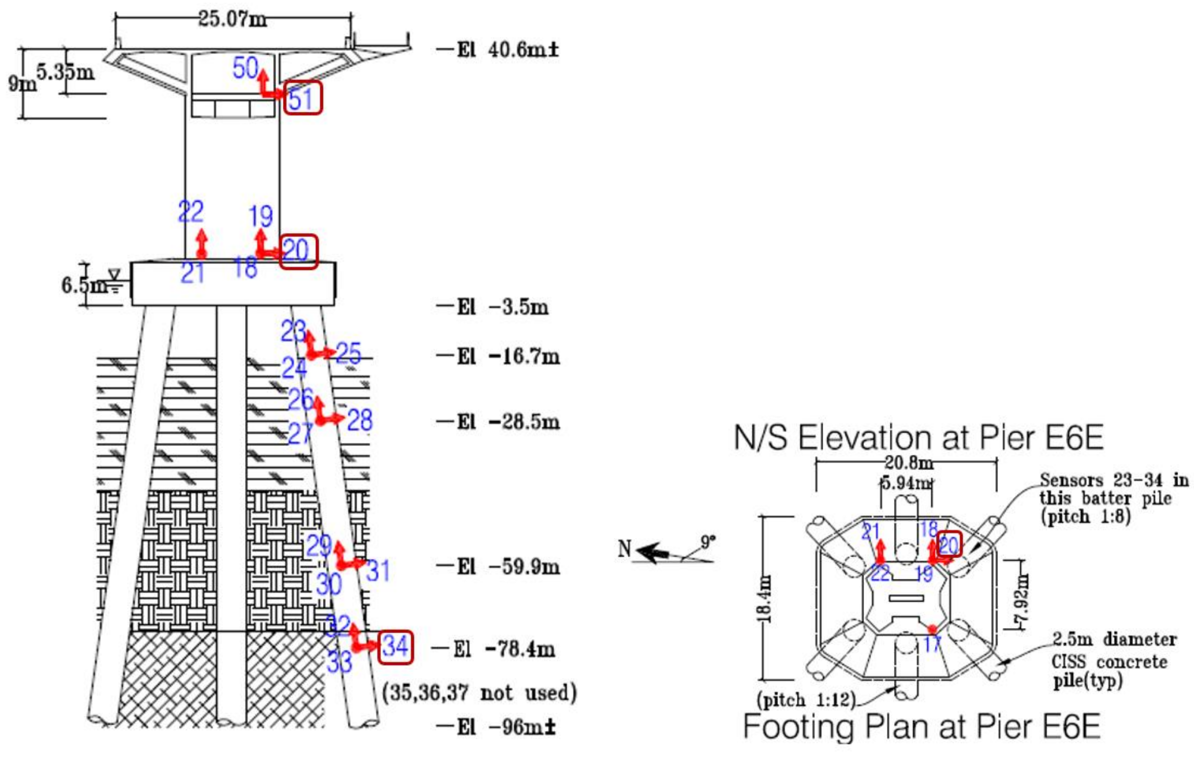
As mentioned, both infrastructures were instrumented with permanently embedded sensor networks. The analysis was carried out on the transverse channels of structures as, in both cases, this represents the (relatively) more flexible direction.

For the Bay Bridge, the station CE58601 from the CESMD Strong Motion Data Set was considered. In particular, this study focuses on Pier E6E since, as mentioned earlier, this is one of the few to have been instrumented throughout its whole height, from the foundation piles to the concrete box girder section.

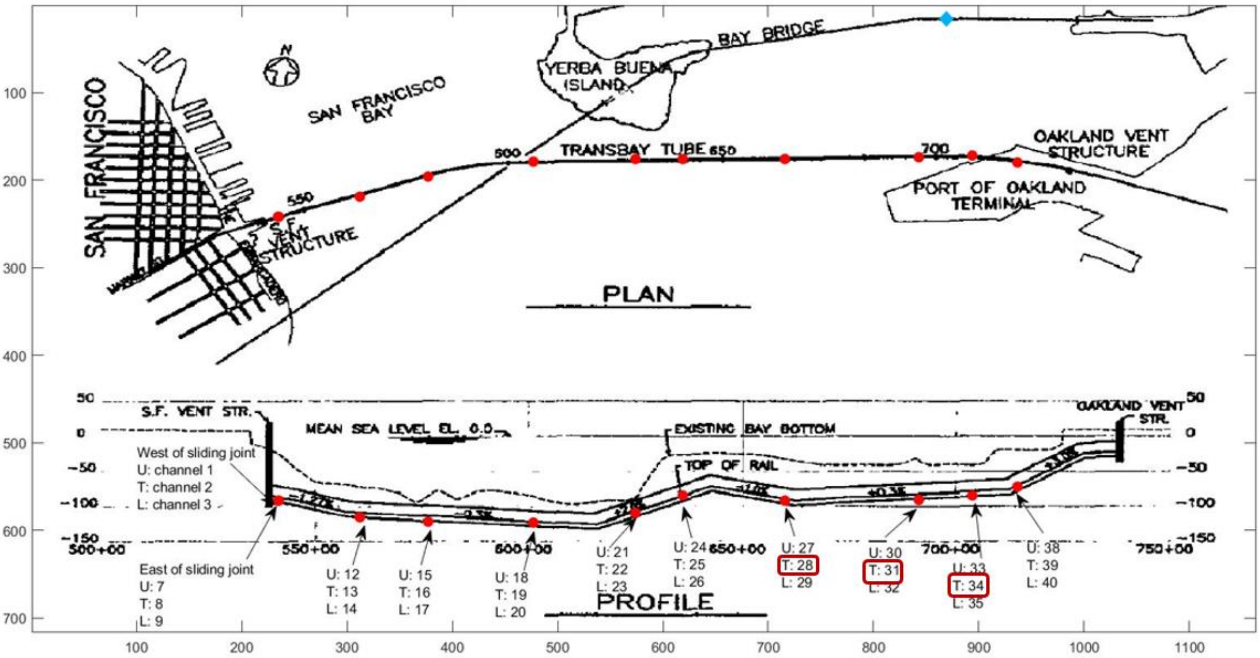
To simplify the comparison process, it was chosen to compare only three representative channels for each structure. Hence, to address the differences between the underground, above-ground, and ground-level parts of the bridge infrastructure, the three channels 20, 34, and 51 (as shown in Figure 2.a) were selected for the bridge pier.

For the Transbay Tunnel, the corresponding station is CE58580. Again, the selection was limited to the transverse channels, in particular those located in the East part of the tunnel, close to the pier under investigation, as shown in Figure 2.b (adapted from (Wu et al., 2003)): channels 28, 31, and 34. Channel 39 was also initially considered but later discarded as its recorded dynamic behaviour diverged significantly from the others, most probably due to its location, very close to the inland tunnel entrance. All the other transverse channels (2, 8, 13, 16, 19, 22, and 25) belong to cross-sections of the Tube situated West of Yerba Buena Island or very close to it and hence too far from the Bay Bridge East section of interest.

In the next section, it will be demonstrated how the data verify the consistency between the dynamic response of the channels selected in the underwater tube and at the deepest locations of the bridge pier's foundations.



(a)



(b)

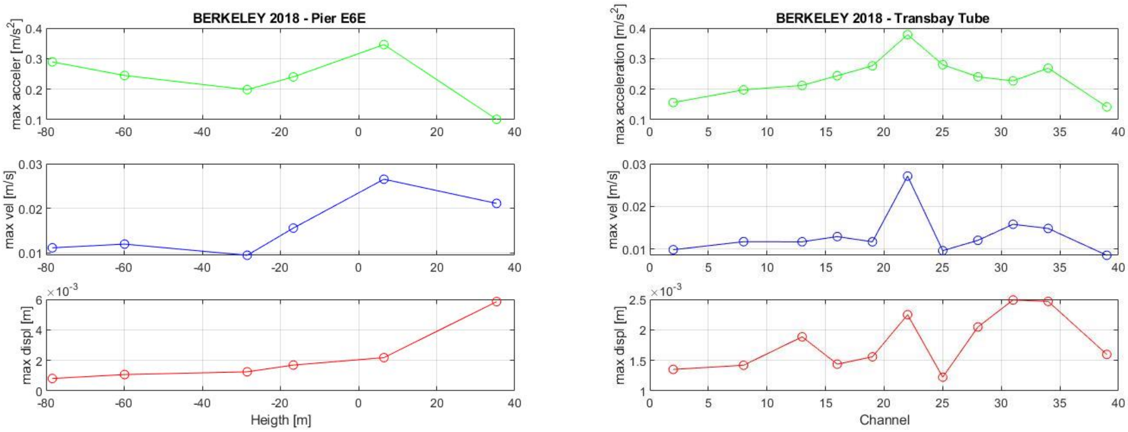
Figure 2: (a) *Bay Bridge's Pier E6E with the position of the channels* ***(b)*** *Top and side view of the BART tunnel with the position of the channels represented with red dots, the light blue diamond depicts the position of the Pier E6E. The channels, that are considered in this study, are highlighted with a red box.*

5. Results

All the data (raw acceleration time series) from both stations (CE58601 and CE58580) were similarly pre-processed, by bandpass filtering the accelerograms with 3 dB pts at 0.30 and 40.00 cyc/sec.

5.1. Preliminary comparison of the recorded data

As a first preliminary study, the dynamic response of Pier E6E (at all heights) was compared to the one of the Transbay Tunnel at all cross-sections. This was mainly intended to verify the assumption that the nearest cross-sections of the Tube were the most similar. This comparison was performed in terms of values of maximum displacement, velocity, and acceleration of each record, as shown in Figures 3.a and 3.b. As can be seen in Figure 3.a, the maximum transverse displacement of the bridge pier is encountered on channel 51, i.e. at the sensor closest to the bridge deck, as well-expected. Similarly, the displacement of underground pile sensors decreases with the depth. One can notice that the maximum displacement at the Transbay Tube's channels 31 and 34 is in the order of magnitude of 2÷2.5 mm, which is mostly in line with what was recorded at the bridge pier channels 25 and 28, which are located at a similar depth and in similar geological layers. The same considerations can be made for the maximum velocity and acceleration as well. These are, overall, relatively stable for the recordings taken at all the cross-sections along the Tube; the only two exceptions are channel 39, which – as said before – is located inland, and channel 22, which is located very close to the ground surface (see Figure 2.b).



(a) **(b)**

Figure 3: (a) *Maximum acceleration, maximum velocity and maximum displacement of each channel located on Pier E6E* ***(b)*** *Maximum acceleration, maximum velocity, and maximum displacement of each channel located along the main direction of the Transbay Tube.*

These preliminary results confirm the applicability of the Transbay Tunnel's channels 28, 31, and 34 for direct comparability with Pier E6E. In the next subsections, the data recorded at the selected output channels will be investigated side by side in the time domain (accelerograms comparison), frequency domain (Fourier spectra), and in terms of Arias Intensity build-up curves (Husid diagrams). The intention is to find the most informative way to directly compare the response of the two nearby infrastructures when undergoing a very similar seismic input, originating from the same event.

5.2. Accelerograms comparison

The accelerations induced by the Berkeley earthquake are visible in Figure 4, starting approximately at 27.5 seconds and continuing until the end of the records (time synchronised between the two stations CE58601 and CE58580 for direct comparability). It can be noted that the maximum acceleration response happens roughly at the same time for both infrastructures, with millisecond accuracy.

The record length of the Transbay Tunnel is 65.835 seconds, which consists of 6584 points equally spaced by Δt=0.010 seconds. The maximum acceleration obtained is the one of channel 34, measuring 0.423 m/s^2.

The record length of Pier E6E is 73.525 seconds, which is composed of 7353 points equally spaced with the same Δt=0.010 seconds. The maximum acceleration is obtained from channel 20, measuring 0.342 m/s^2.

By comparing the behaviour of the two infrastructures, is possible to observe that once the seismic solicitation has concluded, the acceleration of the Transbay Tube response rapidly fades away. Instead, the free vibrations last longer on the pier, moving from the ground (channel 20) up (channel 51). As it will be shown later, this is even more clearly visible in the Husid diagram. The response at the location corresponding to the pile bottom end (channel 34), instead, is very similar to the ones recorded on the underwater tunnel at different nearby locations. Again, these similarities will be reflected in the Arias build-up curves as well.

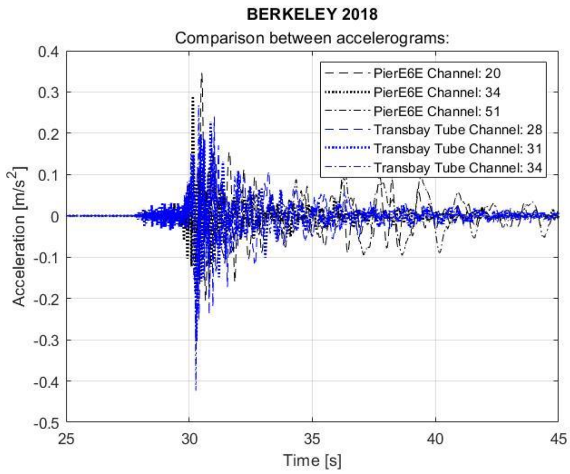


Figure 4*: accelerogram comparison between the channel Pier E6E (black curves) and the Transbay Tube (blue curves). Based on data retrieved from https://www.strongmotioncenter.org/cgi-bin/CESMD/StaEvent.pl?stacode=CE58601.*

5.3. Fourier Spectra comparison

The Fourier spectra analysis, shown in Figure 5, was performed on the signal included between 27.5 and 36 seconds, the portion that corresponds to the seismic motion of the two structures. After that, the data were also filtered, to remove the measurement noise at higher frequencies.

As can be seen from Figure 5, there is no information immediately recognizable by the naked eye. The three channels corresponding to three different heights of Pier E6E behave relatively similarly to the three channels corresponding to three nearby tunnel cross-sections. Apart from some generic statements about the energy distribution in the lowest frequencies (<5 Hz), no specific insight can be directly extrapolated from this visualization of the recorded outputs.

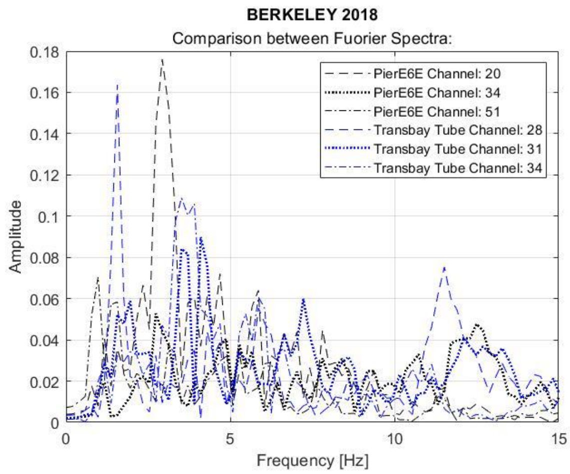


Figure 5: *Fourier Spectra comparison between the channel Pier E6E (black curves) and the Transbay Tube (blue curves).*

5.4. Time-Frequency analysis

For further investigation, a time-frequency analysis of the six recorded responses was performed as well. To create the spectrogram matrix, the following algorithm was followed: the spectrum was divided into 5-second windows overlapped by 2.5 seconds (50% overlap). On each window was applied a baseline correction and a Tuckey window with r=5%. After the Fast Fourier Transform of the windowed signal, the spectrum was smoothed by a 5-point halfwidth moving average. The results are shown in Figure 6. It is possible to notice that, as seen before, there are strong similarities in the frequency content, even if not a totally perfect superposition. The frequency content of the Tunnel responses seems to be always slightly higher than for the bridge pier; also, some higher frequency content is missing at the deck level.

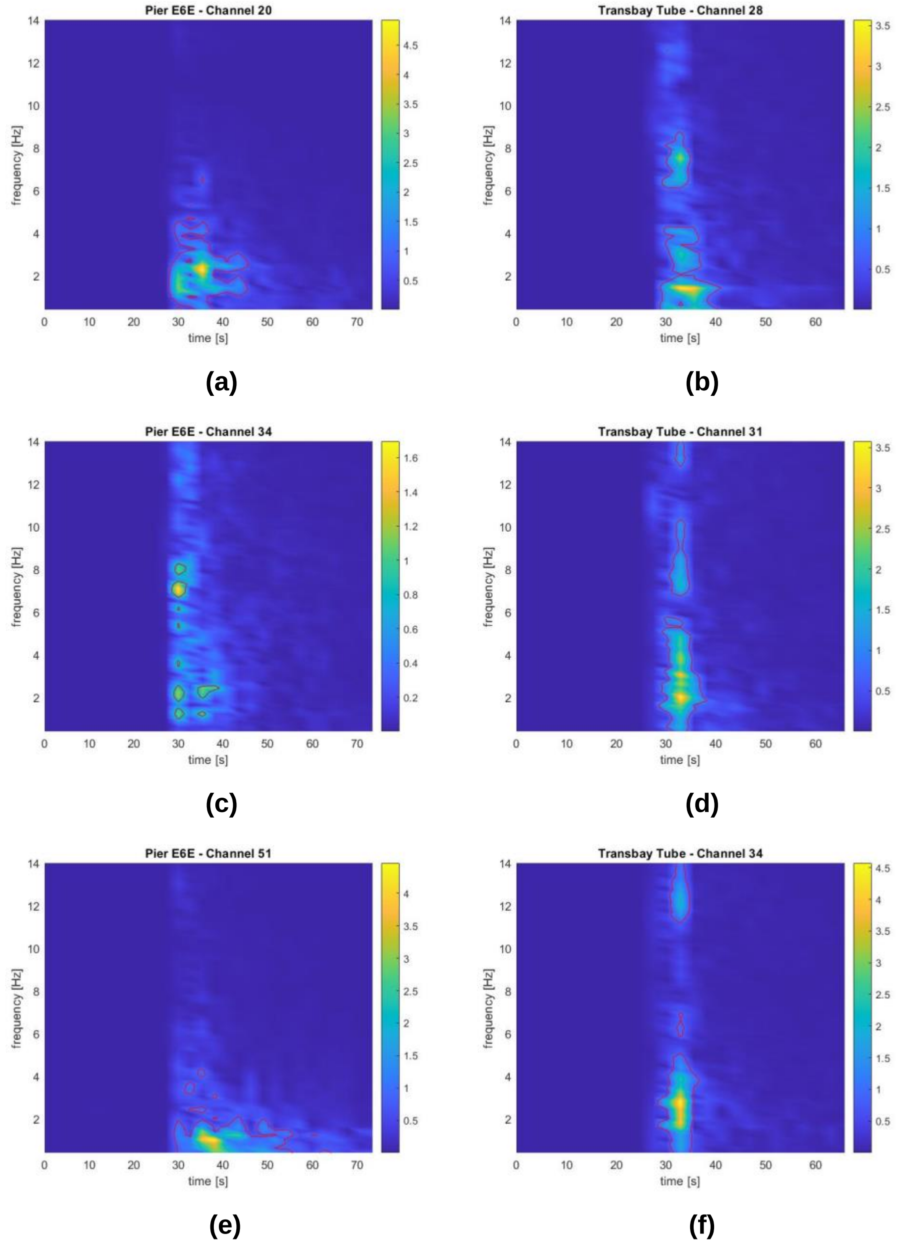


Figure 6. *Seismogram of the channel 20-34-51 of Pier E6E* ***(a), (c), (e),*** *seismogram of the channel 28-31-34 of Transbay Tube* ***(b), (d), (f)****.*

In all the seismograms, the seismic significant duration is slightly different, even if very similar (about ten seconds, mainly contained in the 30-40 seconds range). The only exception is the bridge pier's channel 51 at the deck, which is subjected to a longer solicitation due to the free vibration of the superstructure.

The frequency content is more variable from case to case, with the Transbay Tube's responses having a more widespread distribution at higher frequencies (>8 Hz) almost at all channels. Yet, the frequency content remains relatively almost constant across time for all of these signals, thus not truly justifying the need for time-frequency analysis.

On the other hand, there are distinct differences in amplitude behaviours. For instance, the amplitude decreases much faster for channel 31 of the Transbay Tube than for channel 34 of the Bay Bridge. Conversely, when comparing the other channels, the opposite trend is observed.

As will be shown in the next Section, much of this insight can be assessed by means of the Husid diagram, which only requires a 1D rather than a more advanced 2D analysis and representation.

5.5. Arias Intensity and Husid Diagrams comparison

The Arias intensity build-up curves, also known as Husid diagrams, are an interesting approach to visualise and analyse the structural response to a seismic input. Basically, they represent how the Arias intensity cumulates over time, from 0% to 100%. In turn, the Arias Intensity (AI) (Arias, 1970) is defined as

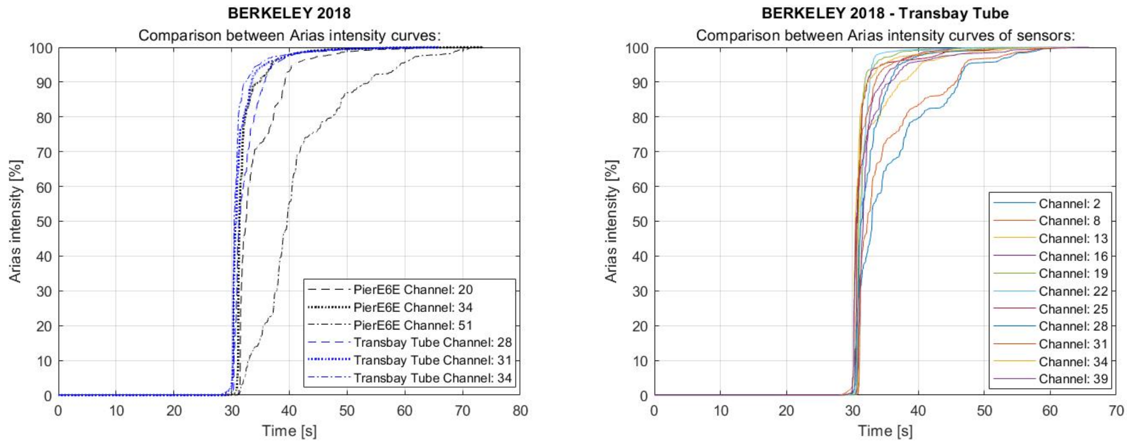
$$\mathrm{AI} = \frac{\pi}{2g}\int_0^{t_{max}} a(t)^2 dt \qquad (1)$$

where $a(t)^2$ is the squared ground acceleration at time t, t_{max} is the maximum duration of the recording (which is implicitly assumed to last longer than the seismic event recorded), and g is the acceleration of gravity. As can be clearly seen from the integral Eq (1), the unit of Arias Intensity is m/s; yet, rather than a physical velocity, this quantity can be better considered as the cumulative energy per unit weight absorbed by an infinite set of undamped single-degree-of-freedom oscillators having a uniform distribution of fundamental frequencies on $(0, \infty)$ (Arias, 1970). What is relevant is that AI is a function of the time-varying ground acceleration amplitude, the frequency content (since the value of the integrand between zero-crossing will be frequency-dependent), and the duration of the ground motion; all factors that are widely considered as directly related to the risk related to a seismic event (Bradley, 2015). In this regard, AI measures have been proven to be strongly correlated to various metrics of seismic response, also in the specific case of bridges (Mackie & Stojadinović, 2001).

Importantly, in several scientific articles – e.g. (Bradley, 2015) – t_{max} is indicated as the length of the seismic event itself; yet this is generally not known a priori. On the contrary, the Arias intensity build-up curves are generally used to estimate the earthquake's so-called *significant* duration, as done for instance in (Dikmen, 2016). In its most common form, known as Ds_{595} (Trifunac & Brady, 1975), this can be computed as the time elapsed in between the two instants when 5% and 95% of the total energy $\int_o^{t_{max}} a(t)^2 dt$ is reached; this definition shows obvious similarities with Equation 1, already pointed out in (Trifunac & Brady, 1975)

From the Arias intensity build-up curves of the analysed accelerograms (Figure 7.a), it is possible to highlight the different behaviours of the two structures. In fact, for the Transbay Tube, which is embedded in the soil and confined by it, the response is quite uniform in space and instantaneous in time. It is also very similar to what can be observed for channel 34 of Pier E6E, which is located in the foundation. This behaviour is similar to the one of a single impulse since the earthquake epicentre is very close to the two infrastructures and the two points are well confined by the surrounding ground, which does not allow for large free vibrations after the initial shock.

In this context, it is also interesting to evaluate the Husid diagrams obtained from the other records of each cross-section of the underwater tunnel, as reported in Figure 7.b. It can be clearly seen how the seismic energy is absorbed in a short period of time for cross-sections nearer to the epicentre (eastern side, closer to Oakland), but the significant duration becomes more and more prolonged moving westward (San Francisco). The fact that the significant duration of the responses at the chosen tunnel cross-sections (channels 28, 31, and 34) is very similar to the one recorded at the bridge pier's pile confirms the adequacy of the selected subset of channels for this analysis.



(a) **(b)**

Figure 7: (a) *Husid diagram comparison between the channel Pier E6E (black) and the Transbay Tube (blue)* ***(b)*** *Husid diagram of all the transverse channels of the Transbay Tunnel.*

For the other bridge pier's channels (i.e. the above-ground ones, not constrained by the surrounding soil), the energy solicitation of the seismic action lasts longer due to the contribution of the free vibration, as could be clearly seen from channel 51 of the Pier in Figure 7.a. A similar trend was observed in the other piers that have been instrumented along their height (E3E, E4E, and E5E, all located in the immediate proximity of E6E).

The actual seismic durations estimated from the curves shown in Figure 7.a are also quantitatively reported in Table 1. These are paired with the corresponding estimates of Arias Intensity for the six cases.

Table 1: Significant duration and Arias Intensity of the selected output channels.

	Pier E6E (Bay Bridge)			**Transbay Tunnel**	
Bay Bridge Channel	**Significant Duration [s]**	**AI [m/s]**	**Tunnel Channel**	**Significant Duration [s]**	**AI [m/s]**
20 (water level)	9.10	0.0073	28 (West)	6.74	0.0044
34 (78.4 m underground)	5.92	0.0022	31 (mid)	5.69	0.0036
51 (bridge deck)	26.97	0.0056	34 (East)	4.65	0.0041

As a main observation, the significant duration for the Transbay Tunnel is almost the same for all the channels analysed yet it slightly increases as the sensor location is located farther from the epicentre. This confirms what is visually seen in Figures 7.a and 7.b. Similarly, the significant duration increases in the bridge pier's above-ground structural components as they move farther from the ground. This second case is much more accentuated, with Ds_{595} at the bridge deck being almost three times longer than the one at the water level (almost five times longer than the one underground). That is easily explainable by the difference in the overall increase in flexibility. The AI is also larger at the top of the superstructure but not with the same large margin as Ds_{595}, if compared to the lower locations along the pier. Instead, the Arias Intensity is almost constant for the three cross-sections along the Tube.

This aspect could also explain the different seismic risks of above- and below-ground infrastructures as, all things being equal, it is well-known that a longer seismic response causes larger structural damage (Jeong & Iwan, 1988).

In this case, the Arias Intensity is not drastically different for the three tunnel channels (circa 0.004) and the bridge deck (circa 0.006); yet this latter one is generally known to be at much higher risk. Even in the specific case considered here, this component of the superstructure was the one actually damaged in the 1989 Loma Prieta earthquake, when neither the Transbay Tube nor the other parts of the bridge above- and belowground structure indicated any other major damage. This also proves that, differently from what was expected, AI on its own failed to indicate the most at-risk location in Pier E6E, as it is larger at the column basis (0.007) than at the top. Yet, the large difference in the significant duration could explain the outcomes of the Loma Prieta event.

However, it should be remarked that the Arias Intensity cannot be seen as a direct indicator of the seismic risk since it does not consider the specific ultimate strengths of the various structural sub-elements. Yet, it can be seen as a direct indicator of the seismic hazard for different infrastructures and/or different sub-elements of the same.

6. Conclusions

The comparison between the seismic behaviour of one underwater tunnel, the Transbay Tube, and one above-ground infrastructure, the Bay Bridge, has been carried out. These two infrastructures represent relevant engineering and architectural works of the XX century, with worldwide fame. They are very close to each other and run almost parallelly East of Yerba Buena Island. The transverse direction was analysed for both cases. A near-fault strong motion (epicentre distance: circa 10 km) has been used, selecting three channels for the bridge (Pier E6E) at three different heights and three channels for the tunnel at three cross-sections.

The analyses aimed to reveal the different behaviour of the two structures when subjected to similar seismic inputs originating from the same source. On the one hand, the visual inspections of the raw time domain and frequency domain data (response time series and respective Fourier Spectra) clearly do not show any interesting features at a glance.

Conversely, the time-frequency analysis returns useful information but at a relatively large computational cost, not truly justified as the frequency content does not change excessively during the whole significant duration of the seismic event.

On the other hand, the Arias intensity (AI) and its build-up curve (a.k.a. the Husid diagram) provide valuable insights into the tunnel and bridge pier responses in a simplified yet effective manner.

In particular, the Husid diagram of the Transbay Tube has a response similar to the one of an impulse, only extending over time when moving away from the epicentre. For a very similar location, this response is very similar to the one recorded at the bottom end of the bridge piles but very different from the one recorded at the channels installed on the top (at the concrete box girder).

When paired with the Arias Intensity, the significant duration obtained from the Husid diagrams can explain the differences in the behaviour of the two infrastructures and, especially, the different robustness of the several structural elements of the bridge. Specifically, it is possible to point out the higher significant duration suffered from the concrete box girder, as recorded by the accelerometer (channel 51) installed on it, with respect to the other channels of the same bridge pier, located near or below ground level. This aspect could explain the common knowledge that bridges are more sensitive to earthquake damage compared to tunnels, as for comparable Arias Intensity (which is a well-known indicator of potential earthquake-induced structural damage), a longer (significant) duration can increase the risk of material failure.

Furthermore, the similarities and differences between the seismic responses of the two nearby infrastructures investigated here will be the basis for further studies and investigations, also due to the ramifications of these aspects for what concerns the post-seismic accumulation of structural damage.

7. Acknowledgments

This work is part of the research activity developed by the authors within the framework of the ‘PNRR’: SPOKE 7 “CCAM, Connected Networks, and Smart Infrastructure” - WP4.

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